AERIS

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16.1. Introduction

In recent years, technological breakthroughs in lasers have widened their applications; they are no longer limited to cutting or welding, and may now be considered for wireless power transmission. Combined with other energy harvesting technologies, using lasers may increase an Unmanned Aerial Vehicle's (UAV) endurance, range and business potential.

As a final year Design Synthesis Project (DSE), a group of 10 students were assigned to design a continuously flying Earth observation UAV that is partially powered by external laser power in 10 weeks. Soon after starting the project, the group named the concept "AERIS", standing for Aerial Research Inspection and Surveillance. The name also alludes to one of the ancient Greek goddesses, Iris, who served as a messenger for the other gods, and is the Latin word for air.

Table 16.1

Project Description Requirements	
SUS-2	At least 20% of the energy used by the system shall come from renewable sources.
GEN-2	The system shall be capable of monitoring every part of the Netherlands.
GEN-3	The operational lifetime shall be at least 5 years.
FPF-1	The UAV shall fly between 50 and 100 km/h.
FPF-2	The UAV shall sustain continuous flight in normal operational and meteorological conditions.
FPF-3	The operational altitude shall be between 100 m and 4000 m.
EQ-2	The UAV shall have a high-resolution spectral camera on-board.
ENE-1	At least 50% of the energy used on-board shall be provided by remote power beaming.
ENE-2	At least 20% of the energy used on-board shall be provided by solar cells.
SAF-3	The UAV shall have a fail-safe emergency landing mode in case of power loss.
ENE-3	Any remaining power shall come from COTS energy harvesting systems.
GST-1	The number of base stations required for remote power shall be minimized.
SUS-6	Noise levels shall respect the norms set by environmental institutes.
FIN-1	Road map and budget for introducing the technology to the market.

Assumed Stakeholder Requirements	
MG-1	Employees shall be employed for the whole mission.
MG-2	Investments shall break even within 3 years of operation.
MG-3	Services shall be in the financial reach of micro-enterprises.
SUS-1	Measures shall be taken to reduce the amount of energy that is used during life-cycle.
SUS-3	The materials used shall be recyclable.
SUS-4	The materials used shall be non-toxic.
EQ-1	There shall be a continuous stream of data available during the entire mission.
GEN-1	In case of failure there shall always be a back-up system of stand-by.
GEN-2	The system shall be capable of monitoring every part of the Netherlands.
MG-4	A manual shall be present, containing all information needed to operate the entire system.
SAF-1	The system shall be capable of avoiding safety hazards such as bird strikes.
SAF-2	The position of the system shall be known at any moment during the mission.
SEC-1	The system shall be protected against theft and vandalism.
SEC-2	Measures shall be taken to reduce the risk of hacking the system.
GOV-1	The system shall operate according to all relevant laws.
GOV-2	The system shall respect each and everyone's privacy rights.
SUS-5	The system shall not cause any harm to wildlife.
GOV-3	Direct stakeholders' privacy shall be respected.
EQ-3	The data link shall provide sufficient data transfer capacity to sustain a live-stream.
SAF-4	The power available for the UAV shall not drop below a critical level, making landing on a safe location possible.
SAF-5	The UAV shall have a collision avoidance system.
SAF-6	The system shall be capable of recognizing weather hazardous to the UAV's operation.

The main project goals were to provide a reliable, sustainable and accessible system capable of accurate and continuous monitoring of urban areas, natural landscapes, coastlines and weather in the Netherlands from 2016 onwards. The mission statement of the project is to "*provide a reliable, sustainable and accessible system capable of accurate and continuous monitoring urban areas, natural landscapes, coastlines and weather in the Netherlands from 2016 onwards*," which directly follows from the mission need statement: "*Mankind needs longer range, more sustainable and more accessible UAV to provide accurate and continuous Earth observation*."

The scope of the project was partially set by the engineering skills learnt by the students prior to this project in their bachelor's degree in Aerospace Engineering, though some additional skills were learnt during the project. The project and additional assumed stakeholder requirements are summarized in Table 16.1.

16.2. Project Initiation

The project began with the proposal of a project plan. This designs the Human Resources (HR) management structure in which team members were assigned to certain roles and responsibilities within the team. The division of roles were made in such a way that each team member would have both technical and non-technical roles during the various design phases of the project. The Work Breakdown Structure (WBS) and Work Flow Diagram (WFD) were created to have a detailed overview of the required activities and the required order of their execution respectively. A detailed project schedule was produced in the form of a Gantt chart to identify the various project phases. The group's design philosophy – in particular its policy on sustainable design – and additional stakeholder requirements that the group expected to account for in a commercial environment were also given in the form of a Requirements Discovery Tree (RDT).

The case study and the project requirements were then researched further, which substantially developed the scope of the project. Monitoring the waterways of the province of Zuid-Holland in the Netherlands would be a priority and the focus of the first years of the proposed business plan. The project's scalability was also considered in the later stages of a five-year business plan where the objective would be to expand to every part of the Netherlands. These aspects and their associated risks were also considered in a risk analysis, and following this certain measures to mitigate those risks were also iterated.

A functional analysis was then performed, resulting in a Function Breakdown Structure (FBS) and a Functional Flow Diagram (FFD). The FFD ensured that all functions are addressed by the design to perform the mission. Meanwhile the FBS served to give a technical overview of the design problem.

16.3. Final Concept Selection

Initially, several design options existed to fulfil mission requirements and objectives. These options were given in the form of a Design Option Tree (DOT) in their respective categories. These categories included UAV types, take-off methods and propulsion types among others. Several options were rather innovative, which really allowed the team to consider the pros and cons of those possible solutions to the fullest extent of their ability. Solutions that were later seen not to comply with the project description and stakeholder requirements were eliminated immediately, and a few were directly traded off.

The design options that remained were then sized to give more concrete information to analyse. Some performance parameters relied on an 'engineering gut' sense, hence they were limited in their importance, as seen in at the bottom of Table 16.2. In this table, the team gave each design option overall scores that had different mathematical definitions. Simply put, the standard weighted sum was simply the sum of each score multiplied by its weight (importance), whilst the conservative and aggressive designs had worst-score and best-score biases respectively. This allowed one to examine discrepancies further that may have gone unnoticed and re-iterate or revise the component scores, allowing one to implement further learning about each design whilst double-checking one's work.

Table 16.2

Parameter	***Importance***	***Glider***	***Flying wing***	***Prandtl wing***	***Zeppelin***
Endurance Vmax [hrs]	0.125	0.34	0.18	0.25	0.22
Endurance Vmin [hrs]	0.100	0.26	0.21	0.25	0.28
V_20 percent solar [km/h]	0.138	0.28	0.22	0.25	0.25
Noise Rating [W]	0.038	0.94	0.78	0.90	0.38
Battery Mass [kg]	0.125	0.94	0.78	0.90	0.37
Structural Mass [kg]	0.025	0.90	0.93	0.94	0.23
Engine Mass [kg]	0.063	0.94	0.78	0.90	0.38
Solar Panel Mass [kg]	0.075	0.94	0.85	0.91	0.30
Total mass [kg]	0.013	0.91	0.85	0.90	0.34
Thermals	0.025	0.03	0.09	0.05	0.83
Laser power [W]	0.088	0.94	0.78	0.90	0.37
Stability	0.038	0.32	0.08	0.28	0.32
Controlability	0.025	0.32	0.36	0.28	0.04
Reliability	0.038	0.43	0.29	0.19	0.10
Cost	0.013	0.37	0.30	0.22	0.11
Maintainability	0.025	0.31	0.35	0.27	0.08
Safety	0.050	0.40	0.28	0.28	0.04
OVERALL SCORES					
Standard weighted sum		0.575	0.468	0.525	0.282
Conservative design		0.281	0.215	0.252	0.249
Aggressive design		0.474	0.367	0.418	0.240

The results of the trade-off in Table 16.2 as well as the lower-level trade-offs are summarized in Table 16.3.

Table 16.3

Functions	**Results**
UAV Types	High Aspect Ratio Glider
Take-Off Configuration	Catapult
Landing	Belly Landing
Power Transmission	Laser
On-board Power Storage	Battery
On-board Power Source	Solar Cells
Propulsion System	Electric Propeller

16.4. AERIS' Characteristics

AERIS is a high aspect ratio glider with a high wing configuration, two fuselages, a vertically inverted V-tail connecting two fuselages and an electric propeller engine positioned behind the wing. The wing is the main load-bearing structures. The subsystems and their most important characteristics shall now be described in the order of the N^2 chart from the payload to the stability and control system.

According to requirement EQ-2, AERIS has an on-board Hyperspectral Imager (HSI). It is able to capture a large portion of the electromagnetic spectrum reflecting from the Earth's surface. Not only is it able to make a high-definition map of the surface, it is also capable of detecting fires, oil leaks, chemical hazards, and natural disasters, not to mention various forms of pollution. The team also added an infrared (IR) camera as an additional payload for night-time monitoring activities when the team realized that the HSI would be unable to function in low-light conditions. The IR camera would, for example, be able to detect fires as well as thermal leakages from homes and businesses on the ground. The IR camera is able to detect objects with temperatures between – 25°C to 160°C. An additional IR camera with the same specifications is used as a sensor for the autonomous detect-and-avoid system on-board the UAV.

Both payload cameras are mounted on a lightweight gimbal system, which has several integrated servos and gyroscopes to provide image stabilization about all three axes. The raw video stream produced by the HSI results in a data rate of 63 [Mbps]. The video stream processed by the payload and safety IR camera results in data rate of 5.2 and 35 [Mbps] respectively.

This data needs to be analysed further at the ground station, requiring a communication system. The communication system of AERIS consists of a transceiver, an Automatic Dependent Surveillance-Broadcast (ADS-B), and a computer for compressing and uncompressing the data from the payload and from the ground respectively. The communication system uses ultra-high frequency band of 2.4 [GHz] to establish connection with the ground station and the uplink commands are sent using a radio signal of frequency 480 [MHz]. The team found that the communications system easily functions over a radius of 60 [km] with a single ground station. The aforementioned computer has a compression ratio of 3:1 to compress the data gathered from the payload before it is transferred to the ground station; this compression is lossless.

The ground station consists of six different segments:

1. The communication segment – consists of an antenna to establish connection with the UAV and transceiver to send and receive data.
2. The control room – consists of a flight control device to control and manage the movement of AERIS, as well as two pilots on stand-by.
3. A data storage facility – consists of computers to analyse the retrieved data.
4. The laser station – consists of a laser, the pointer and a cooling system to remove waste heat from the laser. This will be situated on top of the EWI building at the Delft University of Technology.
5. A workshop for repairs.
6. A launch site – consists of a catapult.

Table 16.4

Functions	***Results***
Wavelength	1064 ± 10 [nm]
Laser Output Power	2000 [W]
Beam Quality	5 ± 3 [mm·rad]
Cooling Water Temperature	15 ± 7.5 [°C]
Width	730 [mm]
Height	1375 [mm]
Depth	1120 [mm]

AERIS' payload and communication subsystems must, of course, be lifted into the air. The wing's sizing began with an airfoil selection. Though there are thousands of airfoils available, it is very difficult to select the best airfoil most suited to AERIS' mission. Hence, a few seemingly appropriate airfoils were chosen and their performance was simulated in XFLR5. These airfoils were the:

- NACA 2410
- NACA 2210
- SA 7035
- HN 1023

The two-dimensional airfoils' performances were plotted against each other to compare them. A trade-off was then performed; the NACA 2210 was found to be the most suitable airfoil with a stall angle of 13 [°], a maximum lift coefficient of 1.35, and maximum glide ratio of 86.

The wing was then sized according to a reiterated total mass after it was assumed that an aspect of 30 would be most suitable – a figure that suggested itself as appropriate in the team's research. The wing was then divided into a number of sections along its span. The contour of each section was then divided into a number of segments, and the aerodynamic forces and moments were calculated for each section.

The propulsion system of AERIS is powered by an electric motor. An efficient propulsion system is most likely key for AERIS' success as it uses the majority of the required power. The efficiency of the engine largely depends on the Revolutions per Minute (RPM), and this in turn is affected by the propeller's angle of twist, chord distribution, radius of the propeller and its shape. The latter was determined by using a rather common Clark Y airfoil, and the remaining parameters were optimized in an iterative multivariate optimization process.

To estimate the radius of the propeller blade, linear momentum theory was used. It was found that the radius of propeller increases with a decrease in exit velocity, which increases the propeller's efficiency. The iterative design of the propeller was terminated when enough thrust was finally produced by the propulsion system. The propeller has a theoretical efficiency of 0.95 [-] with a propeller diameter of 1.00 [m]. The maximum power that the engine has to deliver was determined by its service ceiling, which is located at 4000 [m]; AERIS' take off is made possible with the use of a catapult at the launch site. The thrust required during ascents changes with the change in air density and speed was computed to produce a 3-dimensional rate of climb performance graph.

The ability of AERIS to fly continuously largely depends on the on-board power sources and power storage. The power subsystem provides electrical current at the required voltage to the right location at the right time. AERIS' power subsystem consists of an on-board energy harvesting system, a laser energy collection system, batteries and cables. The solar array depends on the wing surface area, and was assumed to be able to cover 90% of the wing's top surface. The laser panel was attached to the winglets, and its size estimated to be 0.3x0.3 [m]. The battery system on-board AERIS consists of novel Lithium Sulfur (LiS) battery packs as well as a Lithium Polymer (LiPo) emergency pack. Each LiS battery pack has an 8-series 1-parallel configuration (8S1P) which resulted in 16.4 [V] and 10 [Ah] with an estimated mass of 584 [g]. Each of these packs have a capacity of 168 [W h] at Beginning of Life (BOL) and 134.4 [Wh] at the End of Life (EOL). The battery degradation of 20 percent over 2000 cycles was taken into account after which the battery would need to be replaced.

Charging the battery using solar cells is very achievable, whereas charging with the laser panel imposes a limit. LiS batteries possess very high charging efficiency. The maximum charge rate of LiS is 0.25C i.e. the maximum charging time is four hours when the battery is completely empty. During the course of charging, a fluctuation in voltages can occur that may potentially damage other systems, making laser charging relatively risky. The voltage fluctuations and proper voltage distribution to the various subsystems will be regulated with the use of Power Management System (PMS). The required cable sizes to connect each component in the UAV, was sized according to the amount of voltage and amperage used by that component.

Since AERIS will be flying autonomously, its stability and controllability plays a significant role in its mission performance. To make AERIS stable and controllable an inverted V tail was implemented. Two major advantages of this tail are that the tail is outside of the engine wake and that it provides the UAV with a closed structure. Since the design has two booms, the position of the subsystems may result in an asymmetric weight distribution. To minimize this the position of batteries was shifted until the desired plane of symmetry was attained. The effects of margins on centre of gravity travel was analysed to define the effect of changing the mass and position of the batteries and payload. The effect provided a limit on the most aft and the most forward cg location the aircraft is allowed to have while the stability and controllability been ensured. The conventional tail sizing procedure involves an estimation of required horizontal tail and a vertical tail that was later combined to form an inverted V-tail. The V-tail requires less actuators compared to conventional configurations and also combines the function of rudder and elevator in a device called a ruddervator and makes the overall design lighter.

The sizing process of every system and subsystem of AERIS was done by making a MATLAB script. This script resulted in a numerical model. For verification, the analytical values of each module were calculated using the corresponding governing equations. Those analytical values were compared with the numerical results. There exist several other methods to check the code. The checks performed were unit checks, common sense, and engineering intuition as to whether reasonable values were obtained by the code. The numerical model that was built during sizing process was verified for all modules. In every module the numerical results approximated the analytical solution very closely.

A numerical model cannot be fully approved unless it has been validated. One of the most common ways to validate a design is performing live tests. Since AERIS is still a concept these tests cannot be performed yet. Once AERIS had been sized it was modelled in X plane. The numerically sized AERIS successfully flew at different altitudes, flight speeds, weather conditions and angles of attack thereby validating the results obtained from numerical model.

16.5. AERIS in Bigger Picture

Now that AERIS and its subsystems have been sized the weight, dimensions and specifications can be obtained. The wingspan of AERIS is estimated to be 9 [m] with an aspect ratio of 30 [-], a tip chord length of 0.43 [m], root chord length of 0.17 [m] and a surface area of 2.73 [m^2]. To be able to charge up safely with the current pointing accuracy a winglet is applied to the wing with a slightly bigger length than the tip chord length. The propulsion system of AERIS consists of one propeller that can gear between two different engines, one for cruise and one for maximum speed. The propeller is foldable, has a diameter of 1 [m], an angular velocity of 600 RPM and is positioned in between the two booms. To be able to deliver such low angular velocities a gear ratio of 10:1 is used.

The power system of AERIS consists of two systems on board to provide enough energy: Solar cells to harvest the energy from the sun and a laser panel to harvest energy from the laser. The 2500 solar cells are arranged in such a way that it covers 90 [%] of the top wing surface. The maximum power that can be generated by these solar cells equals 535 [W]. This system weighs 1.28 [kg]. The size of the laser panel equals 0.3 x 0.3 [m]. The harvested energy is transferred into 7 batteries and these weigh 4.09 [kg]. The expected Beginning of Life and End of Life endurance for 2000 cycles is estimated to be 7.46 [h] and 6.13 [h] respectively. The distribution of power among several system and subsystem in AERIS is managed by Power Management System (PMS). The width of the antenna cable and laser charging cable is estimated to be 0.1 and 4.1 [mm].

The structure of AERIS consists of two materials: ABS and Titanium. ABS is Acrylonitrile Butadiene Styrene and is good for adding inertia however; it fails to cope with big stresses and with the thin-walled assumption used during the sizing process. Whereas, Titanium holds a good property in terms of strength but is very heavy. Hence, a combination of these two materials is used in both the fuselages and the wing. Resulting in a total structural mass of 3.35 [kg].

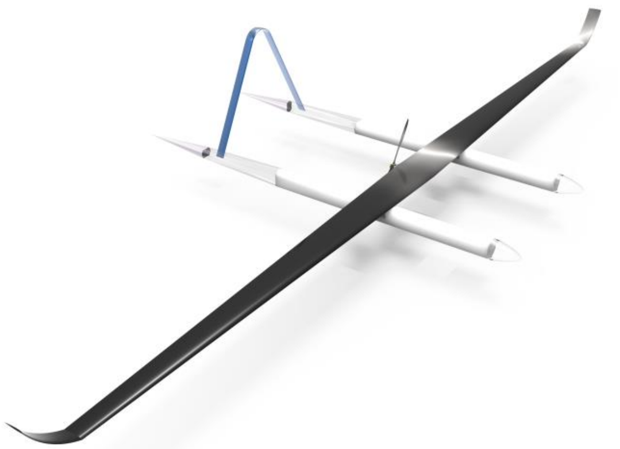

Figure 16.1. Location of various systems and subsystems

Finally, the span of the inverted V-tail is estimated to be 1.5 [m] and has a surface if 0.157 [m^2] with an inverted tail angle of 57.97 [deg]. The total mass of AERIS is calculated to be 12.5 [kg].

16.6. Conclusion and Recommendations

This executive summary marks the end of the design synthesis of AERIS: a UAV capable of continuous flight by using remote power. The project not only considered how to design a partially laser powered continuously flying UAV, it has also respected sustainable development as a key value. It has fulfilled every client requirement with the exception of few requirements that were met partially due to current legislation towards autonomously flying and the lack of completely renewable materials.

AERIS started as a “prestige” project investigating the implementation of external laser power in UAV design. However, analysis of Western markets showed that there are enormous amounts of possibilities and there is a huge market potential, which can be targeted by AERIS to satisfy the needs of several different clients over a range of different industries. Reflecting on AERIS’ conceptual design, external laser power seemed to pose several performance limits to the design, as it is currently not well suited to long-ranged UAV designs. In addition to this, the latest market analysis showed that it would not be especially beneficial to a real design, as it might impose further unnecessary financial risk to potential investors with no outweighing advantage. The external laser power shows a lot of promise in future smaller-ranged UAV design. Not only does it have the potential to broaden the energy mix of future aircraft, it also has the ability to drastically reduce the size of those aircraft by eliminating the need of on-board power storage.

AERIS is not only ambitious because of its external power usage, it is also highly ambitious in its extreme endurance, as well as how it explores and attempts to exploit the advantages of additive manufacturing. The team not only moved away from the conventional wing-box and fuselage designs, it implemented a completely novel design technique to give the most efficient structure to bear loads whilst consuming as little material as possible and thereby keeping the weight down. Even though AERIS has been finalized within the scope of the DSE, several aspects of the design should be investigated in more detail to fine-tune and improve the design. The risk involved within the project should to be mitigated thereby increasing the reliability of the entire system which can be processed by detail analysis of the events identified as “high risk” and by testing the product physically. This will give insight to reassess the safety factors and margins taken into account during sizing several systems and subsystems, which might eventually result in a lighter, higher performing design. During the sizing process, it was assumed that the inflight vibrations on HSI are null and operates with perfect light reflection from the ground. However, this is not the case in real life missions as the weather influences the light reflection from the ground and inflight vibrations occur during the mission. Hence, an extensive research and additional integrated software needs to be included to compensate for the random spectral variations as well as the blur for the varying velocities and altitude settings. To make AERIS able to communicate in every part of the Netherlands, research must be performed to determine the optimum number and location of additional communication stations. The actual effectiveness of the tail shape has to be investigated together with the double engine propulsion system. Apart from these, the possibility of implementing combination of titanium and ABS on the structure of AERIS needs to be investigated. Also real tests on the structure need to be performed to validate the model to ensure that it can sustain the expected loads during its life cycle.

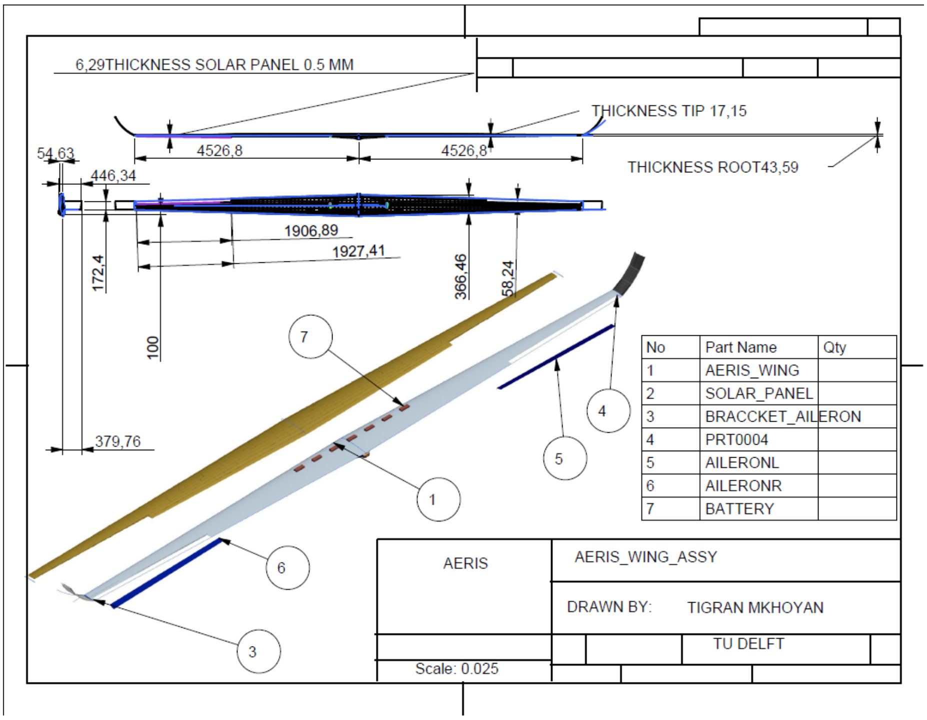

Figure 16.2. Technical Drawing of AERIS' Wing